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ESTIMATES OF PAST AND FUTURE FOREST FIRE DANGER IN FINLAND FROM A CLIMATOLOGICAL VIEWPOINT

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ACADEMIC DISSERTATION in meteorology

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Title
Estimates of past and future forest fire danger in Finland from a climatological viewpoint

Abstract

Roughly three-quarters of Finland's area is covered by forests. Any climatological changes influencing the danger of forest fire are important to evaluate and consider. The objective of this thesis is to study the long-term past and future changes in climatically-driven forest fire danger in Finland based on the summertime mean temperature and precipitation sum.

The work is composed of two parts. In the first part, long-term gridded datasets of observed monthly mean temperatures and precipitation sums for Finland are developed. In the second part, these gridded datasets are used together with calculated values of the Finnish Forest Fire Index and probabilistic climate model simulations (from the ENSEMBLES project) to estimate the number of forest fire danger days during the summer season (June-August). The long-term variation of Finland's climatological forest fire danger is studied roughly for 100 years backwards and into the future. One of the main achievements of this thesis is that it explores the possibility of quantifying past and future fire-weather using a relatively limited database with regard to both weather variables and their spatial coverage. This enables a wider exploitation of scattered data series from earlier times and can also provide opportunities for projections using data with a low resolution.

The climatological forest fire danger in Finland varies considerably from year to year. There have not been any significant increasing or decreasing trends in the number of fire danger days during the 20th century (1908-2011). On average, the highest probability of forest fire danger occurs in June and July, when a fire hazard exists on roughly 35–40% of all days. The intra-seasonal variation of fire danger has been large enough to enable the occurrence of conflagrations even though the fire danger for the season as a whole has been at an average level. Despite the projected increase in average summertime precipitation, the Finnish climate will provide more favourable conditions for the occurrence of forest fires in the future than today. This is due to increases in the mean temperature. The probability of an increase in the number of fire danger days is 56-75% in the near future (2010-2029) and 71-91% by the end of the current century (2080-2099), depending on the region. This would indicate an increase of 1-2 and 7-10 days, respectively.

It is thus clearly important to further develop existing tools for the forecasting of fire danger, and to maintain the capabilities of the fire prevention, surveillance and suppression services. Future projections of all relevant meteorological variables (temperature, precipitation, humidity, evaporation and wind speed) at higher temporal and spatial resolutions, in addition to information on the type of the summertime precipitation and the length of the dry periods, would notably improve the assessment of the future climatological forest fire danger.

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Tekijä(t)
Hanna M. Mäkelä

Nimike
Ilmaston vaikutus metsäpalovaaraan Suomessa

Tiivistelmä

Noin neljännes Suomen pinta-alasta on metsää. Sää ja ilmasto ovat eräitä tärkeitä metsien paloherkkyyteen vaikuttavia tekijöitä. Tässä väitöstyössä tarkastellaan metsäpalovaaran ilmastollisten tekijöiden muutoksia Suomessa sekä menneisyydessä että tulevaisuudessa.

Työ perustuu Suomen kuukausikeskilämpötilan ja sadesumman pitkiin hilamuotoisiin aikasarjoihin, ilmastomallilaskelmiin perustuviin todennäköisyysennusteisiin kesän keskilämpötilasta ja keskimääräisestä sadesummasta Suomessa (ENSEMBLES-hanke), sekä ns. suomalaisen metsäpaloindeksin laskettuihin arvoihin useilta eri suomalaisilta havaintoasemilta. Työssä kehitetty regressiomalli arvioi metsäpalovaarapäivien lukumäärää kesäkauden aikana (kesä-elokuu) perustuen saman ajanjakson keskilämpötilaan ja sadesummaan. Ilmastollisen metsäpalovaaran vaihteluita tarkasteltiin noin 100 vuotta nykyhetkestä taaksepäin ja eteenpäin.

Ilmastollinen metsäpalovaara on pysynyt viimeisen noin sadan vuoden ajan (1908–2011) samalla tasolla. Vuosien välinen vaihtelu on ollut suurta. Myös yhden kesän aikana metsäpalovaara on vaihdellut voimakkaasti siten että suurpaloja on esiintynyt, vaikka kauden metsäpalovaarapäivien lukumäärä on ollut keskimääräinen. Ilmastomallitulokset ennakoivat tulevaisuuden kesien muuttuvan kuluvan vuosisadan aikana lämpimämmiksi ja sateisemmiksi. Ilmastonmuutoksen vaikutus metsäpalovaaraan ei ole itsestään selvä, sillä lämpö lisää metsäpalovaaraa, kun taas sateisuus pienentää sitä. Tulosten mukaan metsäpalovaarapäivien lukumäärä todennäköisesti kasvaa tulevaisuudessa. Todennäköisyys palovaarapäivien lisääntymiseen lähitulevaisuudessa (2010–2029) on 56–75 %, ja vuosisadan loppuun mennessä (2080–2099) 71–91 %; vaihteluvälit kertovat alueellisesta vaihtelusta. Todennäköisyys on suurin Suomen pohjoisosassa, kun muualla maassa se on lähempänä vaihteluvälin alarajaa. Parhaan arvion mukaan keskimääräinen palovaarapäivien lukumäärä lisääntyy seuraavan kahden vuosikymmenen aikana 1-2 päivällä, ja vuosisadan loppuun mennessä 7-10 päivällä.

Näin ollen metsäpalovaaran ennustamiseen käytettävien työkalujen kehittäminen on tärkeää. Yhdessä metsäpalojen torjumiseen käytettävien resurssien ylläpidon kanssa ne edesauttavat pitämään Suomen metsäpalot jatkossakin maltillisena. Alueellisen ja ajallisen tarkkuuden parantaminen tulevaisuuden ilmastoennusteissa, sekä erityisesti kesäsateiden luonteen ja keston tarkempi arvioiminen parantaisi tulevaisuuden ilmastollisen metsäpalovaaran arvioimista huomattavasti. Tarkemman lopputuloksen saavuttamiseksi lämpötilan ja sademäärän ohella myös muut metsäpalovaaran kannalta keskeiset meteorologiset muuttujat, kuten suhteellinen kosteus, haihdunta ja tuulen nopeus, olisi aiheellista huomioida regressiomallissa.

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"Things tend to work out"

Preface

While finishing my master studies at the University of Helsinki in 2006 I applied for a summer job in the Operational Climate Service in the Finnish Meteorological Institute. It was Ari Venäläinen who led the group at that time and decided to employ me. Later that year, he and Heikki Tuomenvirta received a three-year research grant from Kone Foundation for the development of long-term gridded climate data sets. The work was offered for me and with it I got a good foothold in the applied climate research group at FMI. That is where I still stand. So thank you, Ari and Heikki, for choosing me! Getting involved with forest fires, which eventually became the clue of this thesis, happened through an EU project FUME where Ari was leading FMI's share of the work.

This work would not have been accomplished without the help of several people. Most of all I am grateful for my supervisor Ari for his steady and consistent guidance through these years. His calming comments as regards manuscript preparations and especially review processes have been valuable. I want to thank Heikki Tuomenvirta for providing me a lot of guidance for the work related to historical weather records. Heikki Järvinen gave me constructive advises especially when putting pieces together for the introductory part of this thesis. I want to thank Pentti Pirinen who has spent countless hours helping me with different issues related to data handling. I thank all my co-authors, reviewers and other collaborators. Robin King is thanked for helping with the language.

I acknowledge FMI's Research and Development division for providing me working facilities. Head of Unit Hilppa Gregow, Head of Group Niina Niinimäki and all directors before them are acknowledged for providing me working hours for performing and completing the work. I want to thank all staff at the climate service and applied climate research groups at FMI for good working atmosphere. I have never needed to drink my morning cup of coffee or have my lunch alone.

I'm happy for having met wonderful fellow students who later became colleagues and, before anything, good friends. Lastly, I'm grateful for my dear husband Antti for his love, support and encouragement. I doubt whether this work had ever been completed without his help and patience. Finally, our beloved son Tuure has enabled me to take my thoughts from time to time completely away from science and work. My darlings, you are priceless!

Kellokoski, January 2015
Hanna M. Mäkelä

Contents

List of the original publications

This thesis consists of an introductory review, followed by four research articles. The papers are reproduced with the kind permission of the journals concerned. In the introductory part, these papers are cited according to their Roman numerals, as follows:

I. **Tietäväinen, H.**, H. Tuomenvirta, and A. Venäläinen (2010). Annual and seasonal mean temperatures in Finland during the last 160 years based on gridded temperature data. *International Journal of Climatology*, **30** (15), 2247-2256.

II. Ylhäisi, J. S., **H. Tietäväinen**, P. Peltonen-Sainio, A. Venäläinen, J. Eklund, J. Räisänen, and K. Jylhä (2010). Growing season precipitation in Finland under recent and projected climate. *Natural Hazards and Earth System Sciences*, **10**, 1563-1574.

III. **Mäkelä, H. M.**, M. Laapas, and A. Venäläinen (2012). Long-term temporal changes in the occurrence of a high forest fire danger in Finland. *Natural Hazards and Earth System Sciences*, **12**, 2591-2601.

IV. **Mäkelä, H. M.**, A. Venäläinen, K. Jylhä, I. Lehtonen, and H. Gregow (2014). Probabilistic projections of climatological forest fire danger in Finland. *Climate Research*, **60**, 73-85.

1 Introduction

A coniferous forest belt, also known as taiga or boreal forest, covers the northern hemisphere between 50°N and 70°N, with considerable regional variation. The boreal forest is the world's largest land biome, containing 33% of the world's forests (FAO, 2001). These vast forest areas account for more than 30% of all terrestrial carbon present in the carbon cycle and thus have a significant influence on the world's climate (Kasischke, 2000). Forest fires are a natural part of some forest ecosystems, and are essential for the forests' ecological succession and reproduction (Nasi *et al*. 2002). In boreal forests, fire is also a major disturbance, in addition to storms, snow and frost, and insects and fungal diseases (FAO, 2001; Finnish Forest Research Institute, 2014). As well as emitting carbon into the atmosphere, forest fires also reduce the carbon sink in the area by destroying the existing forest, leading to losses in growing stocks (e.g., Bowman *et al*., 2009 and references therein). They can also cause alterations in the hydrological cycle and surface albedo (Bowman *et al.*, 2009; Lyons *et al.,* 2008). Further, the concomitant smoke and fire effluents worsen air quality, and are detrimental to human health (Fowler, 2003; Konovalov *et al.*, 2011).

Relatively speaking, Finland is one of the most-heavily forested countries on earth; three-quarters of its land area (23 million ha) is covered by forests. Its forests are Finland's most important natural resource (Finnish Ministry of Agriculture and Forestry, 2007). Because of the forests' economic importance, fire studies have traditionally been part of forest research in Finland. For example, Saari (1923) already presented a comprehensive investigation into forest fires in Finland, and also Laitakari (1960) included forest fires in his extensive review of the state of Finnish forests over the period 1859-1959.

The forest fire season in Finland starts after the snowmelt in April and ends in September when extended frontal-type rain events become more frequent after the more showery summer months, evaporation decreases and dew formation is enhanced (Tanskanen and Venäläinen, 2008). The main fire season lasts from June till August. During the last 30 years, there have been on average 1000 forest fires annually in Finland, with an average burned area of 0.5 ha per fire. Both the annual number of fires and their burned area are small in Finland because of effective fire prevention and suppression systems (Finnish Ministry of Agriculture and Forestry, 2007). In addition, the established forest fire warnings issued by the authorities together with the high compliance of the general public to these reduces the risk of humanly ignited forest fires during such periods of high forest fire danger. When comparing Finnish forest fires and their prevention and suppression to these in larger, more desolate regions (e.g., in Northern Russia), it is clear that the situation in Finland is easier to control.

The occurrence of a forest fire depends on three elements: suitable weather conditions, flammable fuel and an igniter (e.g., Pyne, 2001):

- Drought, heat and pronounced evapotranspiration dry off organic material in forests, i.e. the fuel, and are thus crucial for producing conditions conducive to fire. Strong wind during and after ignition substantially intensifies spreading of the fire (e.g., Pyne, 2001).

- In forests, ignition of a fire requires in practice dry, dead or live, undergrowth such as mosses, shrubs, brushes, and litter. Tanskanen *et al.* (2005) found that the surface fire ignition conditions are significantly modified by a dominance of *Picea abies* (Norway spruce) or *Pinus sylvestris* (Scots pine) and stand age.

- The majority of forest fires in boreal forests are ignited by humans, typically as a consequence of runaway camp-fires or prescribed burning, or other careless fire handling (Wallenius, 2008). Forest fires do also occur as a result of arson. Practically the only possible natural cause for fire ignition in boreal forests is a lightning strike (Larjavaara *et al.*, 2004). In vast wilderness areas, e.g., in Russia lightning can have substantial role in fire ignition (Gromtsev, 2002), but in Finland, for example, lightning ignites about one hundred forest fires annually, which is only around 10% of all forest fires (Larjavaara et al., 2005).

Due to the last point, the natural forest fire potential, or forest fire danger, does not correlate well with the actually-realized number of fires or the burned area. Human behaviour and socio-economic factors, such as effectiveness of fire detection and suppression systems, are important factors affecting the variation in the occurrence of forest fires (e.g., Bowman *et al.*, 2009, Venäläinen *et al.,* 2014). Thus the number and size of forest fires cannot be explained by the climate, weather or fuel characteristics alone. Inclusion of the causative agents expands the concept of natural fire danger into fire risk (e.g., Hardy *et al.*, 2005).

When considering the effect of climate change on the occurrence of forest fires, higher temperatures and enhanced evapotranspiration will lead to increased fire sensitivity, and in more southern regions, e.g., in the Mediterranean area, the predicted considerable decreases in summertime precipitation will further increase an already-intensified fire hazard (Bedia *et al*., 2014; Mouillot *et al.*, 2002). In Finland, the projections for future summertime precipitation are inconclusive, the magnitude and direction of the change not being explicit (Jylhä *et al.*, 2009). Thus, the effect of the future mean climate on fire sensitivity in Finland is not self-evident. However, previous studies show that the forest fire potential in Finland is about to increase by the end of the 21st century (Kilpeläinen *et al.*, 2010; Lehtonen *et al.*, 2014). According to Kilpeläinen *et al.* (2010), the increased evaporative demand due to higher temperatures will dominate the predicted precipitation increase.

The forest fire danger of the environment is typically assessed using various types of computational indices based on meteorological observation data. These provide evaluation of the environment's flammability. One of the most widely-used fire danger indices in the boreal region is Van Wagner's (1987) Forest Fire Weather Index (FWI) System, developed in Canada. In Finland, the Finnish Meteorological Institute routinely follows conditions for forest fires using an index called the Finnish Forest Fire Index (FFI) (Heikinheimo *et al.*, 1998; Venäläinen and Heikinheimo, 2003, Vajda *et al.*, 2013). When considering long-term studies looking far back into history or into the future, the drawback of forest fire indices is that they typically need input data comprising meteorological variables that are not available on those time scales. Thus, other methodologies have to be applied, e.g., utilizing seasonal climatic values (Duffy *et al.*, 2005; Achard *et al.*, 2008) or information about large-scale climatic patterns (Macias Fauria and Johnson, 2008).

Objectives of this thesis

The main purpose of this thesis is to assess the climate-forced forest fire danger during the 20th century and to provide estimates of the probable magnitude of forest fire danger in the future climate. This issue is studied by exploring the spatial and temporal distribution of the number of days with forest fire danger within the main fire season from June to August. The regional focus of the work is Finland. The topics and material of this thesis are presented in the flow diagram in Fig. 1. The study material is comprised of long-term climate grids of the monthly mean temperature and precipitation sum based on instrumental weather records, probabilistic future climate model projections, and the values of the computational forest fire index from a group of Finnish weather stations. A simple regression model is developed to define the relationship between a summer season's average climate and forest fire danger.

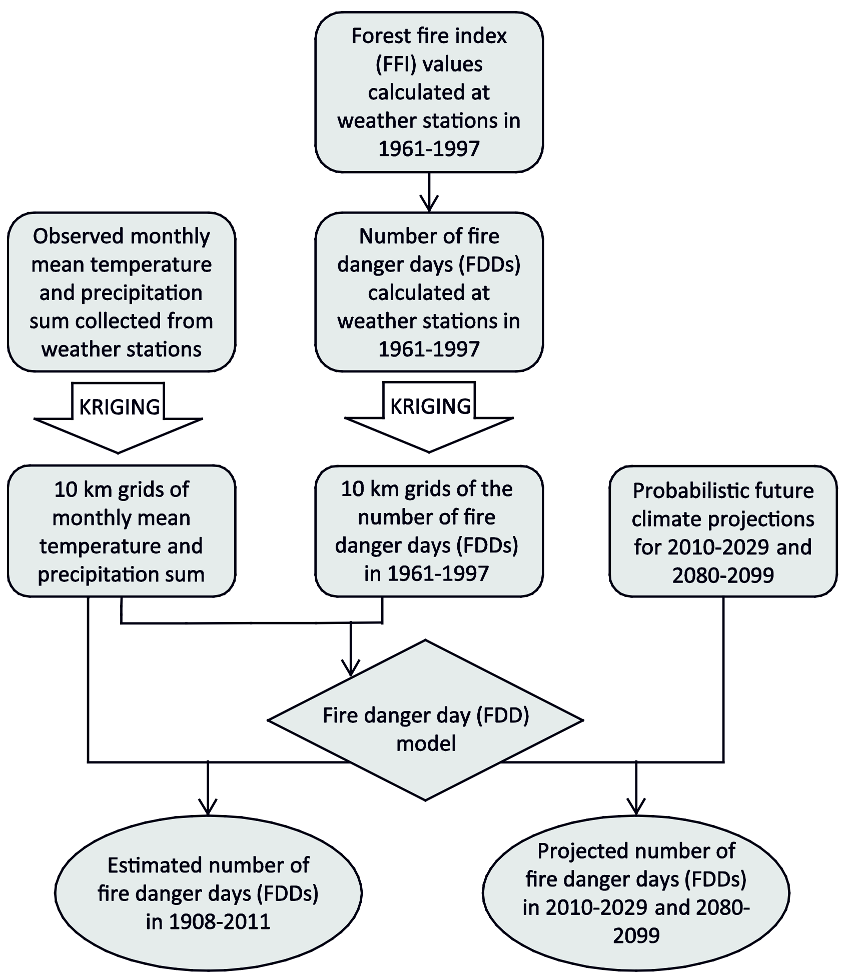

Figure 1. Flow diagram showing the material and topics of the thesis.

To be able to examine the long-term variation in the forest fire danger for roughly 100 years backwards and forwards, climate data having at best a monthly resolution is exploited, instead of using more detailed, daily meteorological values. The knowledge thus gained will eventually enable the assessment of risk levels related to the climatological forest fire danger and the scaling of adaptation measures accordingly. It can also help in the planning of strategies for the fire and rescue services in Finland.

More precisely, the objectives of this thesis are:

- The development and evaluation of the long-term average climate grids of temperature and precipitation with a 10 km resolution over Finland. The gridded data covers the 20th century. (Papers I and II, Section 2 in this introductory part)

- The development of a model describing the relationship between a forest fire season's average climate and the number of fire danger days. Studying the general features of Finland's climatological forest fire danger starting from the early 20th century based on the climatological fire danger model. (Paper III, Sections 3 and 5)

- Estimating the range of possible outcomes for the future fire danger by the end of the 21st century in Finland using probabilistic climate scenarios. Demonstrating the uncertainties in the future projections of Finland's summertime mean temperature and precipitation and their reflection on the climatological forest fire danger. (Paper IV, Sections 4 and 5)

This thesis deals with both past and future time periods, and with observational and modelled data sets. The following sections describe the data sets and methods applied in this thesis one topic at a time. The observed monthly mean temperatures and precipitation sums were used to create long-term historical gridded climate data sets (Section 2). In addition, values of the computational observation-based forest fire index (Section 3) combined with global climate model simulations of temperature and precipitation anomalies for the 21st century (Section 4) were used to study past and present-day features of the forest fire danger (Section 5). The final section consists of the conclusions, together with some thoughts on the direction of future work (Section 6).

2 Development and evaluation of long-term gridded climate data sets

Instrumental monthly weather records

Monthly mean temperatures starting from 1847 and the monthly precipitation totals starting from 1908 from mainly Finnish weather observation stations were collected and used to create long-term gridded mean temperature and precipitation data sets in Papers I and II, respectively. Observational time series from weather stations in Sweden, Norway and Russia near the Finnish border were also used to improve the spatial coverage of the available observations.

In Paper I, temperature time series were collected for each month starting from 1847, when only a few observation stations were available (Helsinki, Kuopio, Kajaani, Oulu, St. Petersburg, Haparanda and Vardö) (Fig. 2). A large set of Finnish monthly mean temperatures were homogenized at the beginning of the 21st century to enable a reliable and meaningful examination of Finland's climate (Tuomenvirta, 2001; 2002). This homogenization procedure followed the Standard Normal Homogeneity Test (SNHT) by Alexandersson (1986) taking into account continuity issues such as those related to changes in the measuring instruments and observing practices, as well as changes in a station's location and its environment. These homogenized monthly mean temperatures were used in this study.

From the late 1860s onwards, the number of available temperature observations from the southern and middle part of the country started to increase (Fig. 3), and from 1908 the first observing stations were established in the northern part of the country, too. Despite the lack of Finnish observation stations in the north, use of temperature data from Swedish, Norwegian, and Russian weather stations enabled an approximation of the mean temperature in Finland already from the mid-1800s to be made. Even though the foreign temperature time series were not homogenized, it was considered that using them would be better than having no observations at all outside the Finnish borders. In any case, all the time series were checked, anyhow, for outliers and other distinct errors.

In Paper II, the observed monthly precipitation sum was collected for the growing season from May till September, starting from 1908 when the precipitation measuring gauge was changed from the so-called Finnish gauge to a Wild gauge, together with a notable increase in the number of observing stations. The Wild gauge was used at all weather stations until 1981/1982, when it was replaced by a Tretyakov gauge. Essentially, both gauge types consisted of a cylindrical vessel and a windshield. Due to an improved windshield the Tretyakov gauge increased the measuring accuracy, especially that of snowfall, during windy weather, whereas for summertime there was no significant difference between the gauges (Heino, 1994). Since then, changes in the precipitation measuring network took place in 1992, when a new measuring instrument (with the same Tretyakov windshield) was brought into operation; furthermore, automation of the observations started during the 1970s.

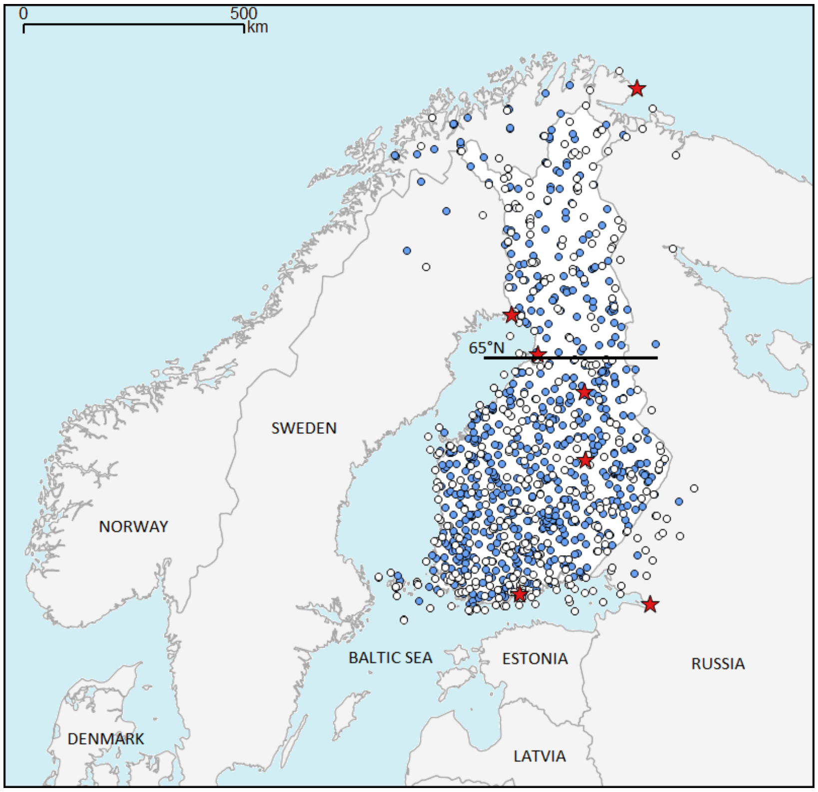

Figure 2. Location of the observation stations providing monthly mean temperature (white circles) and precipitation sum data (blue circles). The first seven temperature stations, already operational in the latter half of the 1840s, are marked with red stars. North of latitude 65°N (shown with a line), gridded precipitation data do not start until 1950.

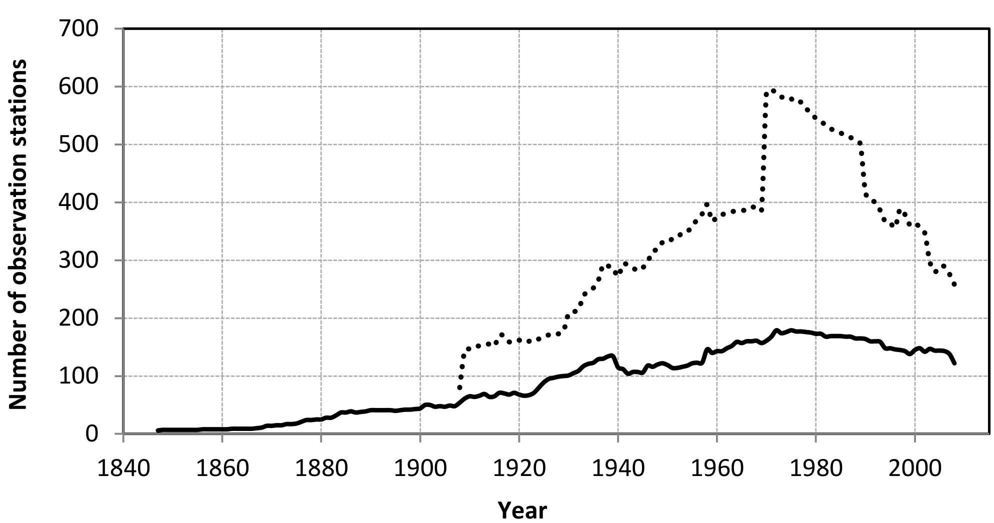

Figure 3. The number of observation stations with monthly mean temperature (solid) and precipitation sum (dotted) data. For precipitation, stations located south of 65°N only are included.

The precipitation amounts given by the measuring gauges are always underestimates of the true rainfall due to, e.g., reduction in the capture of the precipitation particles (due to wind or aerodynamic effects), evaporation from the gauge and spilling and/or adhesion of the water when transferring the precipitation from the gauge to the measuring vessel. Typically, the largest errors arise from the reduced capture of the precipitation (Lemmelä and Solantie, 1977). The Tretyakov gauge was found to measure up to 20-40% higher totals for the monthly precipitation sum during winter months than did the previous Wild gauge (Heino, 1994) because of the improved windshield. The Finnish monthly rainfall time series have not been corrected to be equal to the true precipitation; they thus represent the measured precipitation. The number of observation stations measuring precipitation has traditionally been larger than that for temperature because of the larger spatial variation of precipitation. As in the case of temperature, the precipitation network developed first in the southern and central parts of Finland, and only later in the north. Because of the limited observation network in northern Finland, the monthly precipitation sum time series covering the whole country do not start until 1950. For the southern and central areas of Finland, i.e. that part of Finland located south of latitude 65°N (this boundary is shown with a line in Fig. 2), the collection of the precipitation sum time series used for the development of the climatological grids started in 1908 with 80 stations. By the following year, the number of precipitation stations had already reached 144 (Fig. 3). Monthly precipitation totals were also collected from stations in neighbouring countries near the Finnish border. Because all available observations were used, the station network changed from month to month.

The kriging method for spatial interpolation

To produce gridded data from the monthly mean temperatures and precipitation sums, a spatial interpolation method known as kriging was employed. Several references in the literature related to the development of a similar spatial approximation methodology can be found, but probably the idea of kriging is mostly due to the South African mining engineer D. G. Krige, who applied it in the 1950s. The method was further developed by a French mathematician G. Matheron (1963). Later on, the theory of kriging has also been presented by, e.g., Ripley (1981). Essentially, kriging is a stochastic spatial prediction method that uses information from known locations to predict values at unsampled locations. The predicted surface, i.e., the value of the analyzed parameter (Z) at any location (X), is given as a sum of a trend component *m* and a fluctuation *e*:

$$Z(X) = m(X) + e(X)$$

where the trend component describes the broad-scale features of the interpolated variable and the fluctuation is depicted by a spatial stochastic process that describes the small-scale random variation specific to any given position. Kriging aims to provide the “the best linear unbiased estimation” of the predictable surface at each grid point; it also provides an estimate of the variance of the prediction error (Isaaks and Srivastava, 1989).

Kriging takes into account external forcing factors. The particular kriging model used in this thesis was developed especially for climatological applications in the Finnish environment by Henttonen (1991). Virtually the same version of the model is still currently operational at the Finnish Meteorological Institute and has recently been presented by Aalto *et al*. (2013). In addition to weather observations made in certain locations, it also takes into account the geographical coordinates (*x, y*), elevation of the terrain (*h*), and percentage share of lakes (*l*) and seas (*s*) in each grid box.

$$m(x, y, h, l, s) = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5zy + a_6h + a_7l + a_8s$$

The resolution of the model used here was 10 km, resulting in a total of 3829 grid boxes in Finland.

Because the predicted surface was desired to match the observations at their locations, the so-called nugget parameter was set to zero. The distance over which the observation is taken into account in the prediction (the range parameter) was set to 80 km. Outside this range the predicted surface is adjusted to equal the trend component. The ability of kriging to estimate values at locations with no observations was evaluated by running the model a number of times, omitting one observation station at a time, and then comparing the predicted values at the station locations to the observed values (Fig. 4).

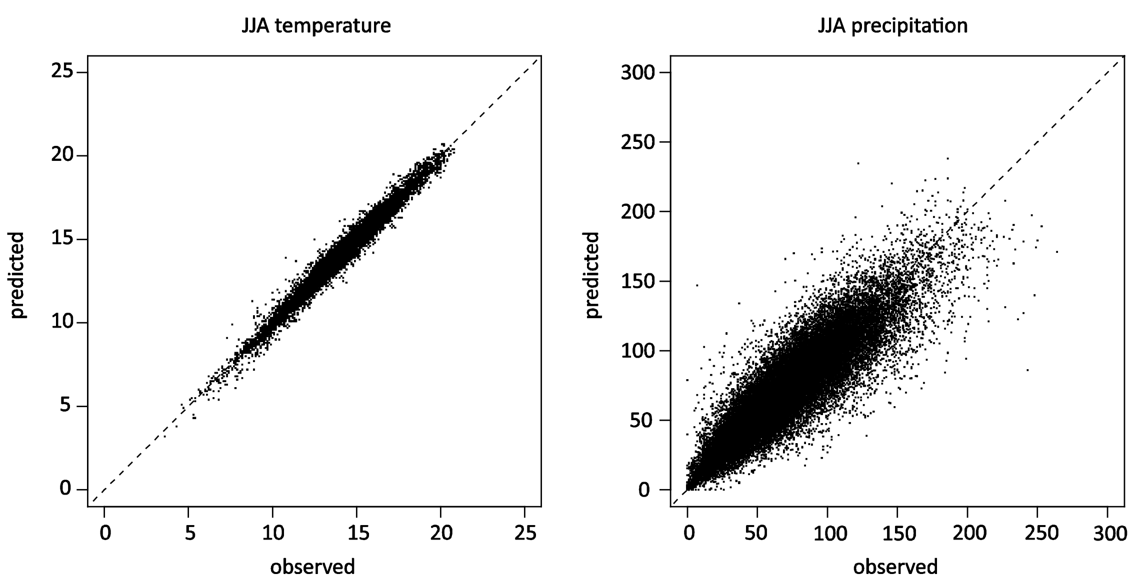

Figure 4. Observed versus predicted (by kriging) monthly mean temperature (°C) (left) and monthly precipitation sum (mm) (right) in June, July and August in 1971-2000 for observation station locations.

Data from all weather stations operational in the reference period 1971-2000 were used for validation, i.e., around 150-180 stations for temperature and from less than 400 to almost 600 stations for precipitation (Fig. 3). In general, the monthly predictions of mean temperature in June-August match the observations well. The mean absolute error (MAE) of the predicted values is 0.29°C, and the mean bias deviation (MBD) -0.21°C, implying that the model slightly underpredicts summertime monthly mean temperatures. For the monthly precipitation sum in June-August the MAE equals 11.35 mm and the MBD 0.49 mm.

Estimation of mean climatological values for Finland

In this thesis, kriging was applied essentially to produce smoothed maps of the broad features of the mean temperature and precipitation sum in order to further calculate the spatial averages over larger areas, e.g., over the whole country. The idea behind this was to achieve better estimates of the national mean temperature and precipitation values compared to direct averages of station values, especially when the station network was limited and strongly concentrated in the southern and middle parts of the country. Because of the low observation density in the 19th century and still in the early decades of the 20th century, the use of individual values of the gridded data would not be sensible. Finland's nation-wide climate averages make use of all the grid points involved in the kriging system, i.e. 3829 grid points in total.

The limited observation station network naturally restricts the ability of the kriging method to predict the temperature and precipitation surfaces with great accuracy. The possible systematic errors and the magnitude of the uncertainty in Finland's mean values related to running kriging with a limited number of observations were evaluated in Papers I and II for temperature and precipitation, respectively. The influence of the limited station network was calculated by running kriging over the 30-year period 1971-2000 with different station combinations imitating the development of the observation network in Finland and comparing these values with those calculated using all the observation stations.

The uncertainty in the summertime (June-August) mean temperature due to the limited station network was ±1.2°C in the mid-1800s, but this decreased quickly with the increase in the number of available stations. At the beginning of the 20th century the uncertainty was approximately ±0.2°C. Values for other seasons and for annual values are presented in Paper I. The error and uncertainty in the mean temperature values are presented as a function of the number of observation stations. However, it is noteworthy that it is not only the number of observation stations but also their location that matters for the success of the spatial prediction. These figures present the error and uncertainty in the mean temperature related to the station network as it has been actually in the course of history. If the same number of observation stations were to have been located in a different way, optimally at uniform intervals, the temperature predictions would have been much more robust.

As the monthly mean temperature time series that were used in the spatial interpolation were homogenized, and thus significant homogeneity breaks would have already been detected and taken into account at that stage, the most important factor contributing to the goodness of the temperature grids was the limited resolution of the station network both in time and space. The uncertainty in the homogenization adjustments made earlier also contributed to a minor extent. Estimates of this are presented in Paper I.

The effect of the limited station network on the gridded precipitation data was evaluated for two sub-regions in Paper II, one located in southwestern Finland and the other in northeastern Finland (see Paper II, Fig. 1 for the regions). It was found that the station network available in the early 20th century provided reasonable estimates of the monthly precipitation sum, especially for the southwestern region; in the northeastern region, however, the uncertainties were larger, most probably due to lower observation station density there as compared to the southwestern region. In the early 20th century the uncertainty in the monthly precipitation sum in the southwest was approximately 10 mm for June, July and August. In the northeast the uncertainties varied from 15 mm (June) to 25 mm (July). However, the uncertainties decreased with the increasing number of observation stations. The average precipitation amount in those areas varied from 65 mm in June to 87 mm in August in the southwestern region and from 53 mm in June to 78 mm in August in the northeastern region.

Average summertime climate in Finland

Based on similar gridded climate data products to those produced in Papers I and II, Finland's average summertime mean temperature and precipitation sum during the latest climatological period 1981-2010 are presented in Fig. 5. Summer is the warmest and, excluding the southernmost part of the country, also the wettest season in Finland. The average mean temperature ranges from 16°C in southern Finland to 10°C in the northernmost regions. In central Finland inland regions are somewhat warmer than the coastal regions.

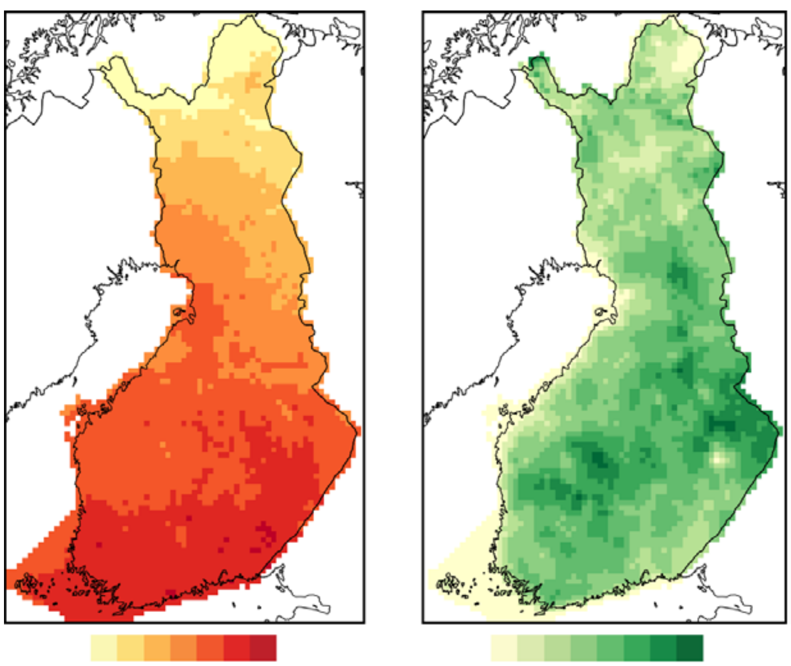

Figure 5. June-August mean temperature (left) and precipitation sum (right) in 1981-2010.

The summertime average precipitation sum is largest, over 240 mm, in certain areas in central and eastern Finland and smallest, less than 170 mm, along the western coast and locally in Lapland. In summertime precipitation falls mainly as showers, which makes the spatial distribution of precipitation somewhat patchy. The thermal summer, defined as the time when the daily average temperature exceeds 10°C, typically lasts for more than the three so-called summer months (June, July and August) in southern Finland but remains much shorter in Lapland. On average, the thermal summer starts at the end of May in the southern part of the country and lasts there till the latter half of September. In Lapland, however, the thermal summer lasts only from mid-June till the latter half of August. Despite these differences, the definition of "summer" as the above-mentioned three months is used to enable a more straightforward analysis.

Because of the early development of the station network in southern Finland, the long-term climate grids developed in this thesis can also be utilized in that area for studies with a higher spatial resolution, even for a single grid point, on condition that there are enough observation stations around the study region. For these kinds of detailed studies it is possible to go back as far as the late 1800s (for temperature). So far, the long-term temperature and precipitation grids developed in Papers I and II have been exploited, e.g., in dendroclimatological and other climate proxy studies (Helama *et al.* 2014a; 2014b; 2013; 2010) and in the studies concerning climate impacts of boreal peatlands' forestation (Lohila *et al.* 2010; Gao *et al.* 2014).

Summary

Spatial interpolation is a way of estimating the values of a desired variable in areas with no observations. Spatially-interpolated climate data serve as basic background information for all climate studies but also for almost any environmental research. In addition, spatially-interpolated climate datasets are widely used in everyday climate services. The accuracy of the spatially-estimated climate fields depends heavily on the reliability of the background observations. With quality-controlled and homogenized station observations, the most important factors affecting the usability of the gridded climate data are the limitations arising from the sparse distribution of observation stations and the length of the observation series.

3 Assessment of climatological forest fire danger

Finnish Forest Fire Index

The Finnish Forest Fire Index (FFI) was developed based on measurements performed during a field campaign in Evo, southern Finland, in the late 1990s (Heikinheimo *et al.*, 1998; Venäläinen and Heikinheimo, 2003). The values of FFI are derived from the estimated moisture change in a 6 cm thick soil surface layer ($m^3\ m^{-3}$), depending upon the precipitation, evaporation and water flow from/into the surface layer. The calculation of the actual evaporation from the surface is based on the product of the drying efficiency and the potential evaporation, the latter being calculated via the Penman-Monteith equation (e.g. Monteith, 1981). The soil surface layer moisture is calculated every three hours exploiting surface observations of air temperature, air humidity and wind speed, the radiation balance obtained via numerical weather prediction analyses and radar-based precipitation amounts.

Recently, Vajda *et al.* (2013) presented a detailed description and evaluation of the performance of FFI in predicting the occurrence of fires. It was found to perform better in the southern than in the northern parts of Finland, due to both the sparser observation network and the lower population density (less fires ignited) in the latter compared with the former. According to Vajda *et al.* (2013), FFI also performed better in predicting days with multiple fires (more than one fire reported) and large fires (burnt area at least 1.2 ha in one fire event) than days with only single, small fires, as the former are less dependent on human behaviour. Vajda *et al.* (2013) compared FFI's performance with one of the most widely-used fire danger evaluation systems in Europe and North America, the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner, 1987). FFI and FWI performed similarly with regards to the observed fire activity in general, the probability of detection of a fire event ranging from 0.3 to near 0.5 for both indices depending on the location (higher values for southern and lower values for northern Finland). This means that less than half of the observed fires are successfully predicted with the fire indices. Regional differences were mainly due to the low population density in northern Finland, due to which fewer fires were ignited and observed there compared to the southern parts of the country.

FFI values range from one (1) to six (6), the lower numbers referring to a lower fire danger and vice versa. A fire danger is considered to exist with FFI ≥ 4. Based on daily FFI values in 1961-1997 calculated for 36 meteorological stations in Finland (Fig. 6), the amount of fire danger days is highest in June, when the probability of FFI ≥ 4 is approximately 40% (Fig. 7). In July the probability for an occurrence of a fire danger day is 35%, in both May and August 20%, in September less than 5% and in April less than 1% (Fig. 7).

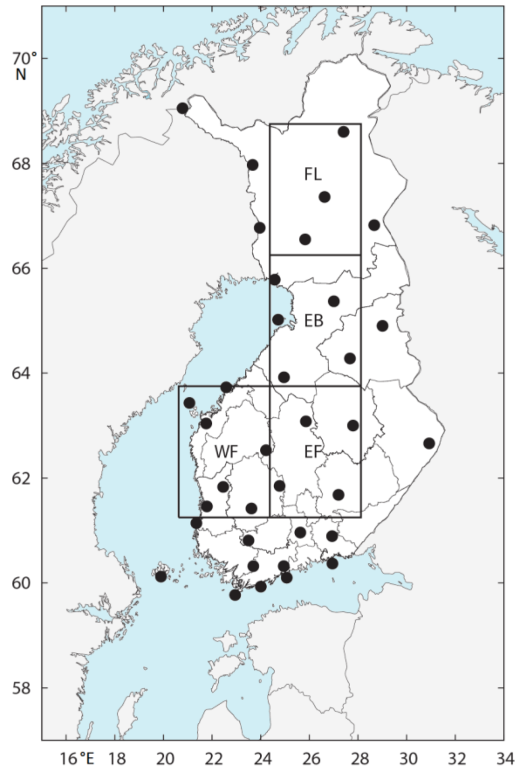

Figure 6. Map showing the locations of the 36 weather observation stations with FFI data. Also shown are the study regions for Paper III: 20 Finnish counties are delineated with a thin black line; for Paper IV: four grid boxes following the resolution of the global climate model HadCM3 (Gordon *et al.* 2010) are denoted with a thick black line; the abbreviations are WF=Western Finland, EF=Eastern Finland, EB=East Bothnia and FL=Finnish Lapland.

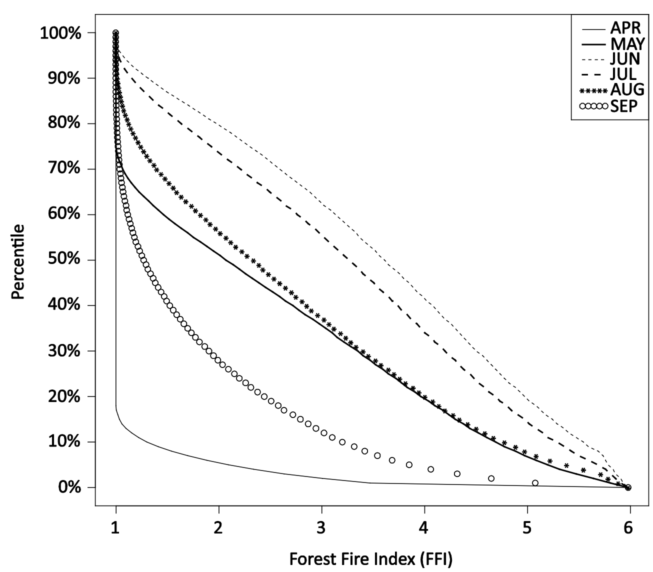

Figure 7. Monthly cumulative percentiles of the Forest Fire Index (FFI) collected from 36 meteorological stations in Finland in 1961-1997. Fire danger is valid with FFI ≥ 4.

Definition of fire danger day (FDD) model

In Papers III and IV, the magnitude of a season's forest fire danger was defined as the sum of the number of days with an existing forest fire danger. The term "fire danger day" (FDD) is defined as a day with an FFI value of four (4) or higher. Further, in Paper III, a group of high fire danger days is selected as being those days when FFI equals five (5) or more. Thus, two different definitions for fire danger days (FDDs) are used:

FDD4 or FDD = the number of days when the FFI is four (4) or higher (fire danger)
FDD5 = the number of days when the FFI is five (5) or higher (high fire danger).

A simple linear multi-regression model predicting the number of fire danger days during a fire season was based on the idea that higher temperatures and lower precipitation amounts lead to a higher number of forest fire danger days during the season, and vice versa. This was formulated as:

$$FDD = aT + bP + c$$

where T and P denote the June-August mean temperature and precipitation sum, respectively (and in Paper IV the anomalies of the June-August mean temperature (ΔT, °C) and precipitation sum (ΔP, %) from their long-term means in 1961-1990). The constants a, b, and c are the regression coefficients. This simple method was chosen in order to be able to study the features of the FDDs in the long term. A more detailed FDD model could include, e.g., daily values of temperature and precipitation, and possibly other variables, too, but those input data are not available for the more distant past and in the modelled future.

The study area covered different regions of Finland. In Paper III the long-term past occurrence of fire danger was studied for 20 Finnish counties, while in Paper IV the future outlook was calculated for four grid cells of the global climate model HadCM3 (Gordon *et al.* 2010). These regions are shown in Fig. 6. Because the sparse station network in northern Finland limited the calculation of precipitation grids for the first half of the 20^{th} century, the long-term FDD time series starting from 1908 were estimated only for that part of Finland located south of 65°N.

The FDD model was fitted during period 1961-1997, for which station-wise FFI values were available from 36 observation stations (Fig. 6). First, the number of fire danger days during June-August was calculated for each station and year. The station FDD values were then interpolated onto a 10-km resolution grid using kriging. From the gridded values areal averages of FDDs were calculated for the desired regions in Papers III and IV and correlated with the areal averages of June-August mean temperature and precipitation sum also calculated from 10-km resolution grids (developed in Papers I and II). In Paper III, the model was fitted separately for FDD4 and FDD5.

The use of linear regression was justified according to the underlying assumptions about the linearity of the dependent and independent variables, the normality and independence of the errors and also homoscedasticity. The normal probability plots and autocorrelation plots of the model error confirmed the validity of the FDD model.

The seasonal number of FDDs is found to have a correlation with the mean temperature and precipitation sum of the same season. It seems that the highest number of FDDs has been achieved not during the warmest, but during the driest summers (Fig. 8).

The FDD model performed best in the southern and western parts of Finland, and poorest in the eastern areas. The goodness of the fit of the FDD model was assessed with the coefficient of determination (R^2) value (adjusted R^2 was used in Paper IV, but the values were virtually the same as for R^2), and the residual standard error (Paper IV). In Paper III, R^2 varied from 0.25 in certain eastern counties to over 0.65 in counties on the southern and western coasts. In Paper IV, R^2 was at its lowest, 0.53, in Finnish Lapland, and around 0.65 in the three other regions. The R^2 values between the two papers were in good agreement. The characteristics of R^2 followed the locations of the observation stations that have been used in developing both the climate grids and the FDD grids. In areas with fewer stations, R^2 was at its lowest possibly relating to the accuracy of the gridded data. The FDD model tended to underestimate the extreme FDD values, the predicted minima being too high and maxima too low (Fig. 9).

Summary

The difficulty of applying computational forest fire indices, such as FFI, employed in this thesis, for long-term studies concerning time periods not in the immediate past or future is that the required input data are typically not available for those time periods. To be able to examine the long-term changes in the occurrence of forest fire danger in Finland, a simple dependence between the number of days with forest fire danger and the average climate of a fire season was looked for. The relationship found turned out to perform better in southern and western Finland compared to the eastern and northern parts. This is most probably related to the sparser observation network in the latter areas compared with the former ones.

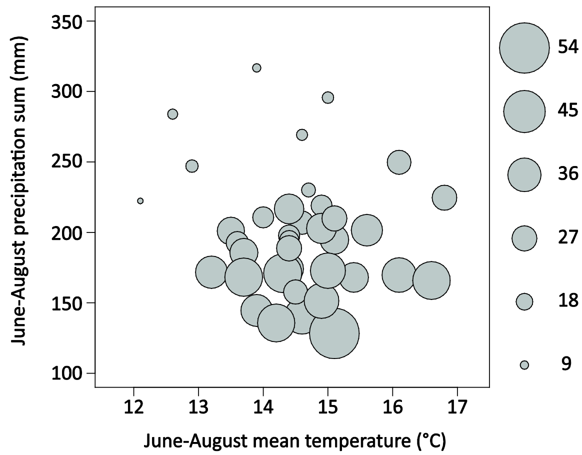

Figure 8. Scatter plot of June-August mean temperature, precipitation sum and number of fire danger days in 1961-1997 south of 65°N. Sizes of the symbols are proportional to the number of FDDs: see the scale on the right of the plot.

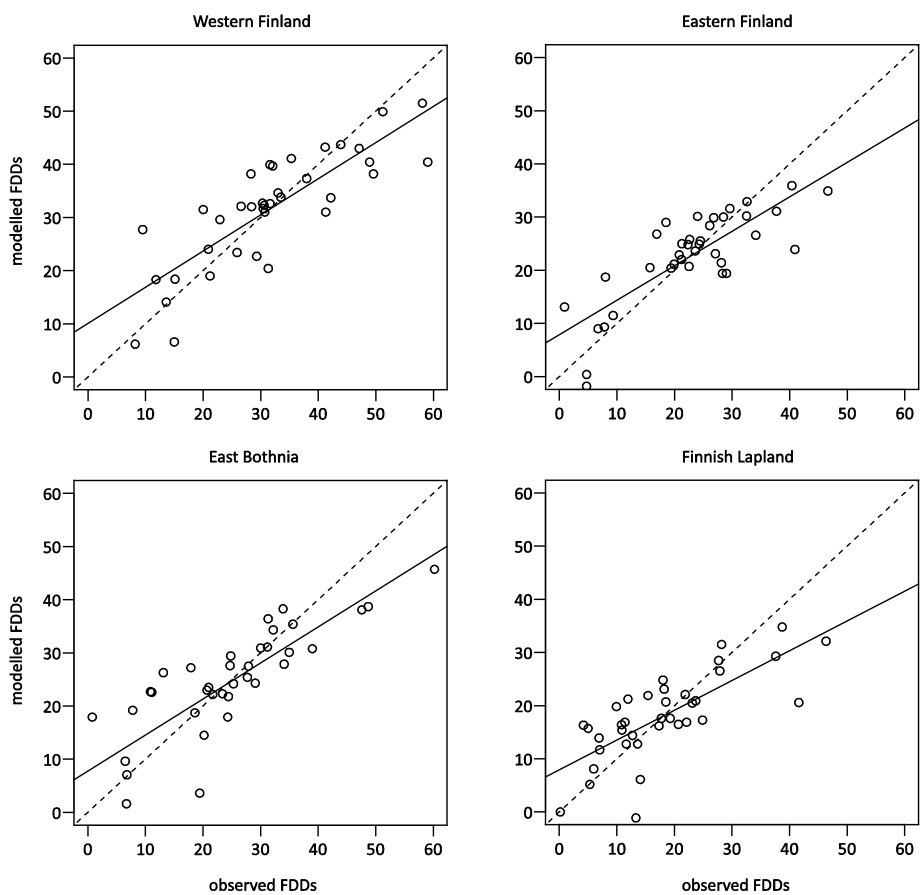

Figure 9. Scatter plots of the observed and modelled number of fire danger days (FDDs) in the study regions in 1961-1997. The solid line shows the best least-squares fit for the points, whereas along the dashed line the number of modelled FDDs equal those observed.

4 Climate scenarios for the 21st century

The ENSEMBLES project (http://www.ensembles-eu.org/) (van der Linden and Mitchell, 2009) produced probabilistic projections of climate for Europe (Hewitt, 2004). The joint probability distribution functions (PDFs) of future seasonal mean changes in surface air temperature (ΔT, in °C) and precipitation (ΔP, in %) from that project (Harris *et al.*, 2010) were downloaded for studying the climatological outlook for forest fire danger in this thesis. A short overview of the future climate PDFs is given here. More information about the climate scenarios can be found in Paper IV, while a complete description of the production of the climate PDFs is given in Harris *et al.* (2010). No future climate model runs were performed specifically as part of this thesis.

The future PDFs are based on an ensemble of 280 simulations performed with the Hadley Centre HadSM3 atmospheric model with a simple slab ocean (Williams *et al.* 2001) supplemented with smaller ensembles using a fully-coupled HadCM3 version with a dynamic ocean model, and sea-ice, aerosol and land-carbon components included (Gordon *et al.* 2000). According to Harris *et al.* (2010), the probabilistic projections quantify uncertainties in the leading physical, chemical and biological feedbacks and combine information from perturbed physics ensembles, multi-model ensembles and observations. The PDFs represent changes in 20-year average temperature and precipitation, expressed as anomalies computed with respect to the 1961-1990 period. The projections follow the A1B emission scenario from the Special Report on Emission Scenarios (SRES) (Nakićenović *et al.*, 2000) by the Intergovernmental Panel on Climate Change (IPCC). The future climate scenarios are available for decadal steps starting from the period 2010-2029 and ending in 2080-2099. For this study, data was chosen for two time periods: for 2010-2029 to represent the present and near-future climate, and for 2080-2099 to represent the climate at the end of this century. Future climate data is available only on a seasonal (three-month' periods) time scale.

The future climate PDFs were provided for each of the 2.5° latitude by 3.75° longitude HadCM3 grid boxes in Europe, resulting in 106 different regions. The spatial scales correspond to a resolution of approximately 300 km. For this study, data was extracted for the four grid boxes falling within the borders of Finland (Fig. 6).

In practice, the future climate data consisted of 10 000 values of future mean temperature and precipitation change for each of the four grid boxes, sampled from the joint PDFs. To achieve greater confidence in the results and following a recommendation of Harris *et al.* (2010), the extremes of the PDFs were mainly ignored, and the 10th and 90th percentiles were used a measure of the spread of the PDFs.

The future climate PDFs show that the Finnish summertime mean temperature is very likely to rise in Finland by the end of the current century. The temperature increase was on average 1.5°C by 2010-2029 and 4.2°C by 2080-2099 compared to the reference period 1961-1990 (Fig. 10). The probabilities for these temperature increases ranged from 95.7% (EF) to 98.5% (FL) in 2010-2029, and from 97.5% (WF) to 100% (FL) in 2080-2099. The extremes depicted by the 10th and 90th percentiles averaged over all regions were 0.5…2.8°C for 2010-2029 and 1.6…7.5°C for 2080-2099. Estimates for future precipitation change were much less consistent than those for temperature. For the earlier time period, 2010-2029, approximately 69% (FL) to 84% (EF) of the sample points were predicted to experience an increase in the season's precipitation sum. By the end the 21st century the precipitation increase was predicted with a 48% (WF) to 80% (EF) probability. The most probable change in the summertime precipitation sum varied from +4.5 % (FL) to +12.5% (EF) in 2010-2029 and from -1.5% (WF) to +19.9% (EF) at the end of the century. The range of the predicted precipitation change was large; in EF the 10th to 90th percentile range spanned from an -8.4% decrease to a 62.8% increase in the summertime precipitation sum in 2080-2099.

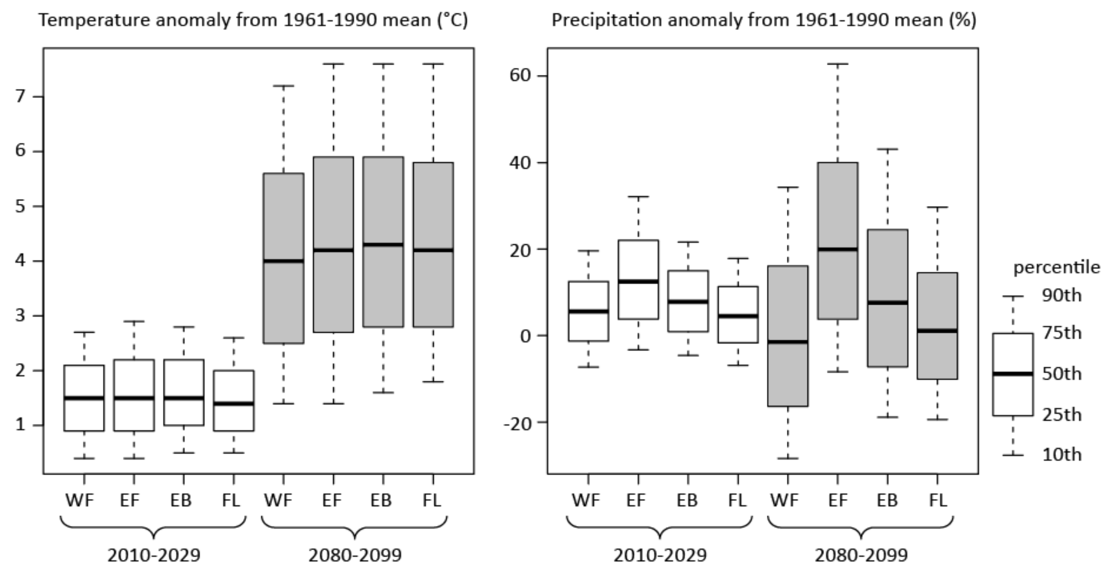

Figure 10. Predicted changes in June-August mean temperature and precipitation sum in each of the study regions according to future climate projections for 2010-2029 (white boxes) and 2080-2099 (grey boxes). The percentiles shown are the 10th, 25th, 50th, 75th and 90th.

The ENSEMBLES temperature and precipitation projections were compared with a range of selected 28 climate models included in the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al.*, *2012*) used in the IPCC's Fifth Assessment Report on climate change (IPCC, 2013). According to a pessimistic emission scenario (RCP8.5), the most probable summertime mean temperature change from 1971-2000 to 2070-2099 in Finland will be around +5°C (+2.5…+7.5°C being the 90% uncertainty interval). According to a more optimistic scenario (RCP4.5) the temperature change by the end of the century will be +3 (+1…+5°C). There are no large differences in the temperature estimates between different regions in Finland. The emission scenario A1B, which is used in this thesis, lies between the RCP4.5 and RCP8.5 scenarios. Correspondingly, the summertime precipitation change in Finland by the end of this century is estimated to be around +10% (-15…+35% being the 90% uncertainty interval) if the RCP8.5 scenario is materialized. Following the RCP4.5 scenario, the precipitation change will be about +9% (-9…+25%).

These numbers are covered by the range of the ENSEMBLES PDF's. Thus the ENSEMBLES joint PDFs give such a wide range of possible future outcomes (the scattered points in Paper IV, Figs. 3 and 4) that they also extend to cover the estimated changes in Finland's summertime mean temperature and precipitation sum according to a wider selection of climate models and different emission scenarios. The foregoing numbers were calculated especially for Finland (unpublished), but similar results, presented in Annex I of the IPCC's report (2013), are given for the whole of Northern Europe.

Finally, to estimate the number of fire danger days in the future, the FDD model was applied for the four study areas with future climate PDFs as input data. As a result, PDFs of future numbers of FDDs were obtained for two time periods: 2010-2029 and 2080-2099.

Summary

To be able to estimate the probable magnitude of the climatological forest fire danger in the future, joint PDFs of summertime mean changes in surface air temperature and precipitation in 2010-2029 (the present and near future climate) and in 2080-2099 (the climate at the end of this century) were adopted from the ENSEMBLES project. By feeding the FDD model with the future climate projections, probability distribution functions of the number of forest fire days in the future were obtained.

5 Effect of climatological factors on the danger of forest fires in the 20th and 21st centuries

In Papers III and IV the climate-forced forest fire danger in Finland was found to be correlated with the fire season's mean temperature and precipitation sum. In Paper III, the characteristics of the forest fire danger were studied for 20 different counties over the period of the past century (Fig. 6). In Paper IV, the future forest fire danger was studied for four grid boxes with a resolution of 2.5 x 3.75 degrees in latitude and longitude (Fig. 6).

General characteristics of forest fire danger in the 20th century

During the latest climatological normal period 1981-2010 the average number of FDD4s in June-August varied between 33-44 days in the coastal counties, between 21-28 days in the central parts of the country and around 15 days in the northern and north-eastern parts of the country (Fig. 11). For FDD5, the corresponding numbers were 16-23 days in the coastal regions, 6-13 days in central Finland, and around 5 days in the north and north-east (Fig. 11). The above-mentioned figures are based on the FDD model. Thus, in areas with the highest numbers of FDDs, a forest fire danger exists on approximately 36-48 % of days in June-August, while a high fire danger (FFI≥5) prevails on 17-25 % of the days. The regional features of FDDs follow by definition those of temperature and precipitation. The summertime mean temperature in Finland decreases northwards, but also the lowest precipitation amounts are observed in the northern part of the country (Fig. 5 in Section 2.).

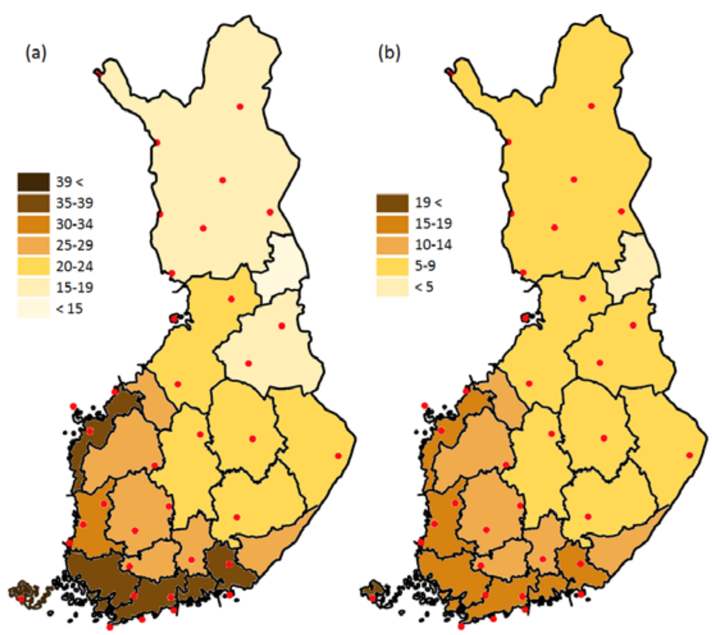

Figure 11. Average number of days in June-August in 1981-2010 when a) FFI≥4 and when b) FFI≥5 according to the FDD model.

These factors have, however, opposite influences on the fire risk. The highest numbers of FDDs occur in the southern and western counties on the coast where it is warmest but where precipitation amounts are also highest. It seems that the high temperatures, and consequently higher evaporation rates, compensate the greater rainfall amounts. The forest fire season is also notably longer in the southern than in the northern parts of the country, enabling the occurrence of more days with fire danger. This agrees with the results of Larjavaara (2004), who reported that the ignition probability is almost threefold in the southwestern part of the country compared to the northeastern parts.

During the 20th century the inter-year variation of the number of FDDs has been large (Fig. 12, bottom panel) and no significant trends could be found. The changes in mean temperature and precipitation sum pull the number of FDDs in opposite directions, both of these factors having increased at the same time.

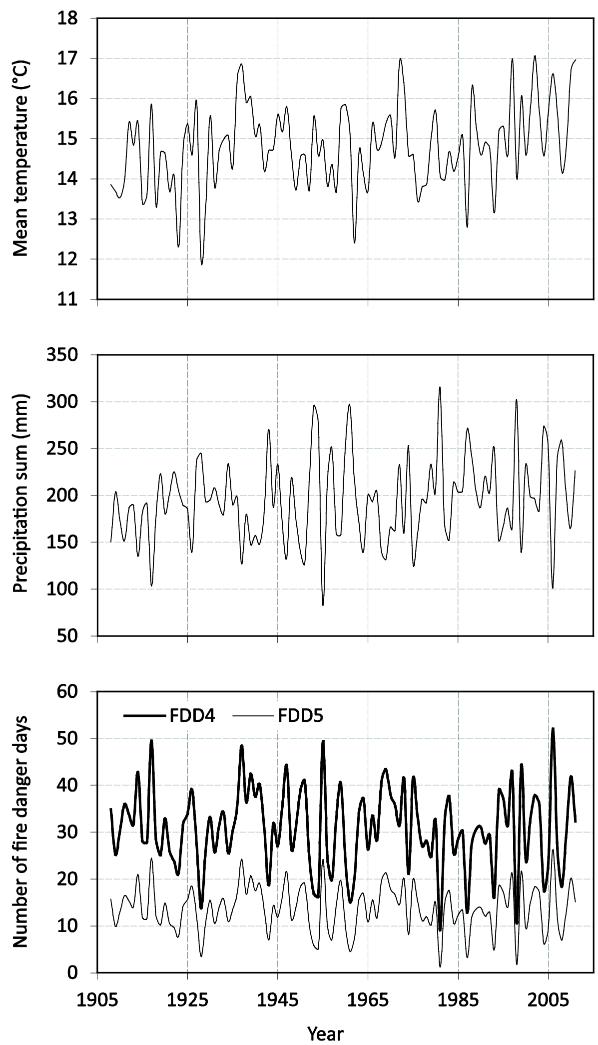

Figure 12. June-August mean temperature (top), precipitation sum (middle) and number of fire danger days FDD4 and FDD5 (bottom) in 1908-2011 south of 65°N.

It seems that the extreme high and low numbers of FDDs occur in seasons with an extreme high or low precipitation sum, respectively, not with an extreme high or low mean temperature. The driest summers of 1955, 2006 and 1917 led to the highest numbers of FDDs, whereas during the wettest seasons 1981 and 1998 the number of FDDs was lowest. These were not the warmest or coolest seasons. The proportion of FDD5s to all fire danger days was at its largest, 50%, in 2006 and 1937, which were both very warm and dry. The highest numbers of FDDs occurred in 2006, when the estimated number of FDDs was 52 (26 for FDD5). These are equal to those of the 500-year return level estimates (Paper III).

The largest known wildfires in Finland occurred in 1960 in the Tuntsa wilderness area of eastern Lapland (burnt area: 20 000 hectares), in 1959 in the Isojoki-Honkajoki area of western Finland (1 700 ha) and in 1970 in Kalajoki, also in western Finland (1 600 ha). Years with the largest wildfires did not stand out from the FDD time series. This indicates that intra-seasonal variations of FDD enable the occurrence of large-scale fires, even though the whole season's fire danger is not particularly high.

21st century projected forest fire danger

Despite the projected general precipitation increase, the average number of FDDs was found to be likely to increase in all study regions. The probability of an FDD increase got larger towards the end of this century (Table 1). The increase in the number of FDDs was most probable in FL (74.5% and 91.4%, for 2010-2029 and 2080-2099, respectively), whereas the lowest probabilities occurred in EF (55.5% and 71.4%).

Table 1. Probabilities for an increase in the June-August number of FDDs in different study regions and for different time periods.

	2010-2029	2080-2099
Western Finland	61.1 %	78.5 %
Eastern Finland	55.5 %	71.4 %
East Bothnia	56.5 %	73.2 %
Finnish Lapland	74.5 %	91.4 %

The most probable predicted change in the number of FDDs varied between 1-2 days by 2010-2029 and 7-10 days by 2080-2099. The largest change was predicted for FL and the smallest for EF for both time periods. Considering the range given by the 10th and 90th percentiles of the PFDs, the predicted change in the average number of FDDs spanned from -8 to +9 days for 2010-2029 and from -10 to +23 days for 2080-2099 (Fig. 13). All the extremes occurred in EF, following the large variation of the precipitation predictions in that area.

The relative increase in the number of FDDs was largest in FL, up to +55% on average by the end of the current century, due to the lower number of FDDs initially. However, in the future the regional distribution of FDDs will be similar to that today: the largest average number of FDDs will occur in WF and the lowest in FL. The predicted change in the number of FDDs would lead to average values of 20 (FL) to 33 (WF) days with a forest fire warning during summer in the near future (2010-2029). By the end of the current century (2080-2099), the average number of days with an elevated fire potential would range from 28 (FL) to 41 (WF) (Table 2).

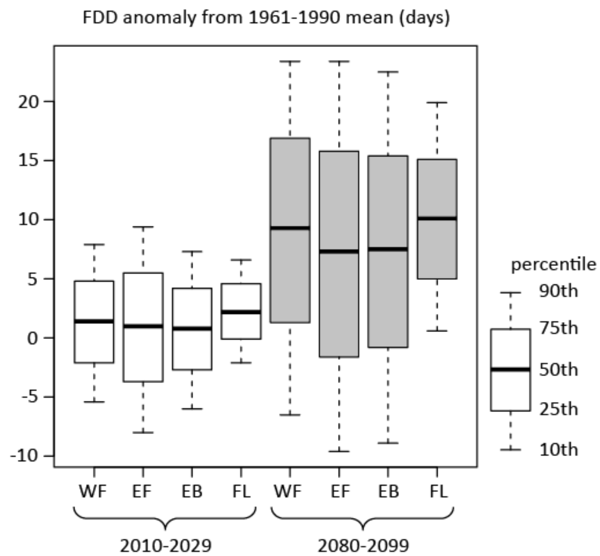

Figure 13. Change (days) in the June-August number of fire danger days (FDDs) in each of the study regions in 2010-2029 (white boxes) and 2080-2099 (grey boxes) relative to 1961-1990. The percentiles shown are 10th, 25th, 50th, 75th and 90th.

Table 2. The predicted number of fire danger days (FDDs) in each of the study regions in 2010-2029 and 2080-2099. The data are the 50th (10th to 90th) percentiles.

	2010-2029	2080-2099
WF	33 (26…39)	41 (25…55)
EF	24 (15…32)	30 (13…46)
EB	25 (18…31)	31 (15…46)
FL	20 (16…25)	28 (19…38)

Summary

A large year-to-year variation in the number of FDDs has occurred during the 20th century, and no increasing or decreasing tendencies can be found. The summers with the largest known forest fires did not stand out from the long-term FDD time series, indicating that the variation of climate-forced forest fire danger within a season can be large enough to mask the periods with conditions leading to a conflagration. Despite the general increase in precipitation, the number of FDDs is likely to increase in future. The average increase is largest in northern Finland at the end of the present century (+10 days). However, due to the higher number of FDDs in southern than northern Finland in the current (or recent past) climate, the largest numbers of FDDs will also still occur in the southwestern part of the country in the future (41 days on average by the end of the present century).

6 Conclusions and future work

This thesis contributes to an understanding of the climatically-driven forest fire danger in northern European boreal forests during the past and future several decades. The keynote of the study was to find any long-term changes in the climate-forced forest fire danger in Finland (Paper III) and its possible outcomes for the future (Paper IV). Long-term mean temperature and precipitation grids (Papers I and II) and forest fire index (FFI) data collected from weather stations were used as input information for these studies. One of the main accomplishments of this thesis is that it shows the possibility of quantifying past and future fire-weather using a limited database both with regard to weather variables and spatial coverage. This allows for a wider exploitation of scattered data series from earlier times and also permits the use of low-resolution future climate projections.

This study showed that the fire sensitivity of Finnish forests regarding climatological preconditions has on average stayed the same throughout the 20th century. The year-to-year variation of the number of fire danger days in June-August has been large. Also, the intra-seasonal variation of fire danger is large enough to permit the occurrence of conflagrations even though the season's fire danger is at an average level. In Finland the number of fire danger days is likely to increase in the future. The highest probability for the increase and (relatively) the largest change will occur in areas with the least FDDs at present, i.e., in northern Finland. The projected average number of FDDs in FL in 2080-2099 is estimated to be 28 compared to the present 18 days. The probability for an FDD increase in FL during this century is 91% and the 10th to 90th percentiles of the FDD change range from 19 to 38 days. The lowest probabilities for an FDD increase, and also the largest uncertainties in the future FDD estimates were in eastern Finland, where the number of FDDs is likely to increase with a 71% probability by 2080-2099. The average number of FDDs would then be 30 compared to the present 23. However, the estimates of the change in the number of FDDs in EF by the end of the present century range from -10 days to +23 days. The large uncertainties stem from the uncertainties in the future precipitation projections, whereas the temperature projections are more consistent (an increase in temperature in future leading to an increase in the number of FDDs).

The results obtained are in accordance with previous studies concerning past and future changes in fire potential. For example, Venäläinen *et al.* (2014) found no obvious trend in fire danger in Finland or Northern Europe over the latter half of the 20th century, using the Canadian Fire Weather Index (FWI). For the future, both Lehtonen *et al.* (2014) and Kilpeläinen *et al.* (2010) have estimated the number of days with elevated forest fire danger to increase by the end of this century, the amount of the increase depending on the methods and emission scenarios used.

The main drawbacks of the methods used in this thesis relate to the coarse temporal resolution of the input data, and further to the simplicity of the FDD model. However, to be able to study long-term time series of forest fire danger, simple input data with a coarse time resolution (seasonal data instead of monthly or, in particular, daily data) and simple study methods had to be used. One of the main objectives of this study was to demonstrate the uncertainty in future projections of Finland's summertime mean temperature and precipitation and its reflection on the climatological forest fire danger, and this target was achieved with the present data and methods. Replacing the applied FDD model with a more complex model but still using the same input data would hardly have produced any better results. To argue for the use of the ordinary least-squares method, the same calculations were performed using a robust regression, which is less sensitive to certain violations of assumptions concerning the input data, but the results were virtually the same. In Paper IV, an adjusted R^2 was used to assess the goodness-of-fit of the model instead of R^2 applied in Paper III. The advantage of the adjusted R^2 is that it allows multiple independent variables in a model without spurious improvement of the fit. However, this barely influenced the results.

The major shortcoming of the FDD model was that it tended to even out the FDD distribution, i.e., to overestimate the minima and underestimate the maxima. The future estimates also indicated that climate change is moving FDD towards higher mean values, i.e., towards the area where the FDD model tended to underestimate. Taken together these points give one reason to suspect that the estimates of the high extremes in the mean number of FDDs are probably moderate rather than exaggerated. It is also important to keep in mind that the estimated future numbers of FDDs are mean values for a 20-year period and that the year-to-year variation of FDDs is large. Thus, during a single season and under favourable circumstances, the number of FDDs could be considerably higher than the estimates given in this thesis.

In using the same FDD model for the whole study period, the assumption is made that the precipitation climate at the end of 21st century will similar to that in the reference period 1961-1990. However, studies by Jylhä *et al.* (2009) and Lehtonen *et al.* (2014b) suggest that even though the summertime precipitation totals show increasing tendencies, the number of rainy days would not necessarily increase, and the length of the dry periods might even get longer. Karl and Knight (1998), too, showed that the increase in precipitation that has taken place since 1910 in the United States is reflected primarily in the heavy and extreme daily precipitation events. The forest fire potential is crucially controlled by the temporal and spatial distribution of precipitation, and lengthening of the dry periods increases the fire danger. Large precipitation amounts pouring down during heavy showers do not wet the surface as effectively as the same rain amount falling as frontal precipitation over a longer time period.

The decision to use future climate projections following only one emission scenario (A1B from SRES, Nakićenović *et al.* 2000) stemmed from the fact that the ENSEMBLES joint PDFs of future seasonal-mean changes in temperature and precipitation were made available for that emission scenario only. However, the predicted changes in Finnish summertime mean climate obtained in this thesis were compared with the results of several climate models and emission scenarios. This revealed that the range of possible outcomes for the future climate given by the ENSEMBLES PDFs actually cover those given by the broader selection of climate models. A probabilistic approach for the climate projections was chosen in order to reach a comprehensive evaluation of the possible future outcomes for the fire danger. Using more emission scenarios would most probably have had some influence on the fire danger probabilities and the breadth of the distributions obtained (i.e., making them even wider).

When looking at the fire season as a whole, it is also important to consider the share of fire danger days occurring in May and its future prospects. Based on Fig. 7, the Forest Fire Index (FFI) reaches the limit for a forest fire hazard warning (FFI≥4) in May as often as in August, and lower values of FFI (FFI=1…3) occur even more often in May than in August. Considering that the end of the snow season is expected to take place earlier in the future than today (Ruosteenoja *et al.*, 2011; Räisänen and Eklund, 2012), the fire season can also be expected to start earlier. The increase in the number of FDDs during May can be noteworthy. Tanskanen and Venäläinen (2008) have already found indications of the fire activity shifting towards the spring.

It is important to understand that the objective of this thesis was to estimate the potential fire danger only in terms of the climatological conditions. Many more factors than just weather and/or climate contribute to the realized number of fires and burned area: human behaviour, the efficiency of the fire surveillance and suppression systems, and the characteristics of the fuel load (e.g., Wallenius, 2008; Bowman *et al.*, 2009; Venäläinen *et al.*, 2014) are also significant. For example, Wallenius (2011) found that the steep decline in forest fires in coniferous forests about a century ago could not be connected to any climatological forcing, but was most likely due to changes in human behaviour. The purpose of this thesis was not to use the results obtained to provide tools for estimating the number of fires or the burned area, but to estimate whether the climatological conditions favourable for fires, that is, the fire potential, are increasing or decreasing in the future. It is then up to many other factors whether, in the end, the number of fires increases or decreases.

Finally, here are listed some interesting points which should be included in further studies in this field of work:

- Projections of future precipitation at a higher temporal and spatial resolution would improve the assessment of the future forest fire danger. Information on the type of summertime precipitation (frontal or shower) and the length of the dry seasons would be highly important as regards studies concerning the climatological fire danger.

- An improved FDD model and its more robust validation would need extensive FFI-data from a longer time period. As a comparison, the presented method used partly overlapping periods for model fitting and validation.

- The FDD model would improve substantially by the use of more detailed input data as regards time resolution, and also by the use of more input variables: relative humidity, potential evaporation and wind speed in addition to temperature and precipitation.

- What are the anticipated changes in the Finnish thunderstorm climate; will there be more lightning-ignited forest fires? An increased number of lightning flashes suggests more outbreaks of forest fires, especially if the thunderstorms occur after prolonged dry seasons.

- Gridded observed climate data will become even more important as important background material in many environmental research fields. Furthermore, gridded climate data will probably be also exploited in the operational routines of climate services. Ensuring the high quality of gridded climate data requires the use of high-quality, homogenized weather observations as input data for the interpolation procedures. The comprehensive homogenization of weather observations and climate time series therefore continues to be an important field of work within climate research in the future.

It is clear that for a forested country such as Finland, any climatological changes in the forest fire risk are important to evaluate and consider. At present, the results suggest that the future climate in Finland will provide more favourable conditions for the occurrence of forest fires than today. It is therefore important to further develop tools for the forecasting of fire danger, and to maintain the capabilities of the fire prevention, surveillance and suppression services.

Summaries of the original publications

The contents of Papers I-IV and the author's contribution are shortly outlined below.

I **Tietäväinen, H.**, H. Tuomenvirta, and A. Venäläinen (2010). Annual and seasonal mean temperatures in Finland during the last 160 years based on gridded temperature data. *International Journal of Climatology*, **30** (15), 2247-2256.

PAPER I describes the development of monthly mean temperature grids (10 km resolution) for Finland and the calculation of the Finnish mean temperature based on the gridded data. Because homogenized monthly mean temperatures were used, the most important factor affecting the accuracy of the interpolated data was the uneven distribution of the available observation stations both in time and space. The uncertainty in the annual mean temperature of Finland due to a limited station network was approximately ±1.0°C in the mid-1800s, falling to around ±0.2°C at the beginning of the 20th century. A linear increase in Finland's annual mean temperature was significant during the study period 1909-2008. Throughout the 20th century (1909-2008) the temperature increase was largest during spring, but during the latter half of the century (1959-2008) winters had warmed up the most.

The author was responsible for all the calculations, data analysis and writing.

II Ylhäisi, J. S., **H. Tietäväinen**, P. Peltonen-Sainio, A. Venäläinen, J. Eklund, J. Räisänen, and K. Jylhä (2010). Growing season precipitation in Finland under recent and projected climate. *Natural Hazards and Earth System Sciences*, **10**, 1563-1574.

PAPER II presents long-term trends for the past and future growing season (May-September) precipitation for two regions in Finland. A gridded monthly precipitation dataset of 10 km resolution for Finland was developed for this study, and its description and validation is given in the appendix of the paper. The past long-term tendencies in precipitation were mostly insignificant to give either any major support or challenge to crop production in Finland. According to model projections for the future, a precipitation increase is expected for most of the growing season. Enhanced rainfall early in the growing season would be favourable for the Finnish crop production; however, it is uncertain whether the projected future precipitation increases are sufficient to compensate the increased demand for evapotranspiration. As for the latter half of the growing season, the possible precipitation increases are mostly harmful for the harvest and quality of the seed crops.

The author was responsible for creating and analyzing the observed monthly precipitation grids, for the data analysis and writing concerning the observed precipitation, and for minor part of the data analysis and writing concerning the future precipitation (not those concerning crop production).

III **Mäkelä, H. M.**, M. Laapas, and A. Venäläinen (2012). Long-term temporal changes in the occurrence of a high forest fire danger in Finland. *Natural Hazards and Earth System Sciences*, **12**, 2591-2601.

PAPER III examines long-term changes in the climatological forest fire danger in Finland. The wildfire season's (June-August) fire danger was estimated using the season's mean temperature and precipitation. During the study period (1908-2011) the inter-annual variation in fire danger was large, and no significant increasing or decreasing tendencies were found. Simultaneous, mostly insignificant increases in rainfall caused slight negative slopes for the fire danger. Years with known major conflagrations did not stand out from the fire danger time series, which implies that the intra-seasonal variation in fire danger is large enough to allow the occurrence of large fires, even though the whole season's fire danger is on an average level.

The author was responsible for all the calculations, data analysis and writing, except those concerning extreme value analysis.

IV **Mäkelä, H. M.**, A. Venäläinen, K. Jylhä, I. Lehtonen, and H. Gregow (2014). Probabilistic projections of climatological forest fire danger in Finland. *Climate Research*, **60**, 73-85.

PAPER IV evaluates the future climatological forest fire danger in Finland using probabilistic climate projections. The calculations were based on a simple fire danger day model that exploits seasonal mean temperature and precipitation anomalies to estimate the average number of days with a high forest fire danger during the fire season (June-August). Despite the general precipitation increase, the average fire danger was estimated to increase in the future. The probability of the fire danger increase was 56…75% during the nearest decades and 71…91% by the end of the century, depending on the study region. The increase was strongest in northern Finland and smallest in eastern Finland. Better estimates of the spatial and temporal distribution of future summertime precipitation would make the assessment of future fire danger more robust.

The author was responsible for all the calculations, data analysis and writing.

The author was solely responsible for the introductory part of this thesis.

References

Aalto J, Pirinen P, Heikkinen J, Venäläinen A. 2013: Spatial interpolation of monthly climate data for Finland: comparing the performance of kriging and generalized additive models. *Theoretical and Applied Climatology* **112**: 99-111.

Achard F, Eva HD, Mollicone D, Beuchle R. 2008: The effect of climate anomalies and human ignition factor on wildfires in Russian boreal forests. *Philosophical Transactions of the Royal Society B* **363**: 2331-2339, doi:10.1098/rstb.2007.2203.

Alexandersson H. 1986: A homogeneity test applied to precipitation data. *Journal of Climatology* **6**: 661-675.

Bedia J., Herrera S, Camia A, Moreno JM, Gutiérrez JM. 2014: Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios. *Climatic Change* **122**: 185-199.

Bowman D, Balch K, Artaxo P, Bond W, Carlson J, Cochrane M, D'Antonio C, DeFries R, Doyle J, Harrison S, Johnston F, Keeley J, Krawchuk M, Kull C, Marston J, Moritz M, Prentice C, Roos C, Scott A, Swetnam T, Der Werf G, Pyne S. 2009: Fire in the Earth System. *Science* **324:** 481–484.

Duffy A, Walsh JE, Graham JM, Mann DH, Scott Rupp T. 2005: Impacts of large-scale atmospheric-ocean variability on Alaskan fire season severity. *Ecological Applications* **15**(4): 1317-1330.

FAO. 2001: State of the World's Forests. Food and Agriculture Organization of the United Nations. Rome, Italy.

Finnish Forest Research Institute. 2014: Metsätuhot vuonna 2013. (eds. Heino E, Pouttu A). Metlan työraportteja/Working Papers of the Finnish Forest Research Institute **295**. http://www.metla.fi/julkaisut/workingpapers/2014/mwp295.htm.

Finnish Forest Research Institute. 2013: Finnish Statistical Yearbook of Forestry 2013 (ed. Ylitalo E), Vammalan kirjapaino, Sastamala 2013.

Finnish Ministry of Agriculture and Forestry 2007: Suomen metsät. Kestävän metsätalouden kriteereihin ja indikaattoreihin perustuen. Maa- ja metsätalousministeriön asettaman asiantuntijaryhmän loppuraportti. Maa- ja metsätalousministeriö 7/2007. Vammalan kirjapaino Oy, Sastamala 2007.

Fowler CT. 2003: Human health impacts of forest fires in the Southern United States: a literature review. *Journal of Ecological Anthropology* **7**: 39−63.

Gao Y, Markkanen T, Backman L, Henttonen HM, Pietikäinen J-P, Mäkelä HM, Laaksonen A. 2014: Biogeophysical impacts of peatland forestation on regional climate changes in Finland. *Biogeosciences Discussions* **11**: 11249-11291, doi:10.5194/bgd-11-11249-2014.

Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, Johns TC, Mitchell JFB, Wood RA. 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics* **16**: 147-168.

Gromtsev A. 2002: Natural disturbance dynamics in the boreal forests of European Russia: a review. *Silva Fennica* **36**(1): 41–55.

Hardy CC. 2005: Wildland fire hazard and risk: Problems, definitions, and context. *Forest Ecology and Management* **211**: 73-82, doi:10.1016/j.foreco.2005.01.029.

Harris G, Collins M, Sexton D, Murphy J, Booth B. 2010: Probabilistic projections for 21st century European climate. *Natural Hazards and Earth System Sciences* **10**: 2009-2020, doi:10.5194/nhess-10-2009-1010.

Heino R. 1994: Climate in Finland during the period of meteorological observations. Contributions No. 12. Finnish Meteorological Institute, Helsinki.

Heikinheimo M, Venäläinen A, Tourula T. 1998: A soil moisture index for the assessment of forest fire potential in the boreal zone. In Proceedings of the International Symposium on Applied Agrometeorology and Agroclimatology (Volos, Greece), Office for Official Publications of the European Commission (Luxembourg), (ed. Dalezios NR), EUR 18328-COST 77, 79, 711; 549–555.

Helama S, Läänelaid A, Raisio J, Mäkelä HM, Hilasvuori E, Jungner H, Sonninen E. 2014a: Oak decline analyzed using intraannual radial growth indices, δ13C series and climate data from a rural hemiboreal landscape in southwesternmost Finland. *Environmental Monitoring and Assessment* **186**(8): 4697-4708.

Helama S, Vartiainen M, Holopainen J, Mäkelä HM, Kolströ T, Meriläinen J. 2014b: A palaeotemperature record for the Finnish Lakeland based on microdensitometric variations in tree rings. *Geochronometria* **41**(3): 265-277.

Helama S, Arentoft BW, Collin-Haubensak O, Hyslop MD, Brandstrup CK, Mäkelä HM, Tian Q, Wilson R. 2013: Dendroclimatic signals deduced from riparian versus upland forest interior pines in North Carelia, Finland. *Ecological Research* **28**: 1019-1028, doi: 10.1007/s11284-013-1084-3.

Helama S, Läänelaid A, Tietäväinen H, Macias Fauria M, Kukkonen IT, Holopainen J, Nielsen JK, Valovirta I. 2010: Late Holocene climatic variability reconstructed from incremental data from pines and pearl mussels – a multiproxy comparison of air and subsurface temperatures. *Boreas* **39**(4): 734-748, doi:10.1111/j.1502-3885.2010.00165.x.

Henttonen H. 1991: Kriging in interpolating July mean temperatures and precipitation sums. Reports from the Department of Statistics. University of Jyväskylä, 12.

Hewitt CD. 2004: Ensembles-based predictions of climate changes and their impacts. *Eos, Transactions American Geophysical Union* **85**(52): 566–566, doi:10.1029/2004EO520005.

IPCC. 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (eds. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Isaaks EH, Srivastava RM. 1989: An introduction to applied geostatistics. Oxford University Press, New York.

Jylhä K, Ruosteenoja K, Räisänen J, Venäläinen A, Tuomenvirta H, Ruokolainen L, Saku S, Seitola T. 2009: The changing climate in Finland: estimates for adaptation studies (in Finnish with English abstract, extended abstract and captions for figures and tables). ACCLIM project report, Report 4, Finnish Meteorological Institute, Helsinki.

Karl TR, Knight RW. 1998: Secular trends in precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society* **79:** 231-241.

Kasischke ES. 2000: Boreal ecosystems in the global carbon cycle. In: Kasischke ES and Stocks BJ (eds.), Fire, climate change and carbon cycling in the boreal forest. Ecological Studies Series, Springer-Verlag, New York, NY, p 19−30.

Kilpeläinen A, Kellomäki S, Strandman H, Venäläinen A. 2010: Climate change impacts on forest fire potential in boreal conditions in Finland. *Climatic Change* **103**: 383−398.

Konovalov IB, Beekman M, Kuznetsova IN, Yurova A, Zvyagintsev AM. 2011: Atmospheric impacts of the 2010 Russian wildfires: intergrating modelling and measurements of an extreme pollution episode in Moscow region. *Atmospheric Chemistry and Physics* **11**: 10031−10056.

Laitakari E. 1960: Metsähallinnon vuosisataistaival 1859-1959. Metsäpalot ja niiden torjunta. *Silva Fennica* **107**: 89–94.

Larjavaara M, Kuuluvainen T, Tanskanen H, Venäläinen A. 2004: Variation in forest fire ignition probability in Finland. *Silva Fennica* **38**(3): 253-266.

Larjavaara M, Kuuluvainen T, Rita H. 2005: Spatial distribution of lightning-ignited forest fires in Finland. *Forest Ecology and Management* **208**(1-3): 177-188.

Lehtonen I, Ruosteenoja K, Venäläinen A, Gregow H. 2014a: The projected 21st century forest fire risk in Finland under different greenhouse gas scenarios. *Boreal Environment Research* **19**: 127-139.

Lehtonen I, Ruosteenoja K, Jylhä K. 2014b: Projected changes in European extreme precipitation indices on the basis of global and regional climate model ensembles. *International Journal of Climatology* **34**: 1208-1222.

Lemmelä R, Solantie R. 1977: Maps of Finland's water balance elements. *Nordic Hydrology* **8**: 281-288.

Lohila A, Minkkinen K, Laine J, Savolainen I, Tuovinen J, Korhonen L, Laurila T, Tietäväinen H, Laaksonen A. 2010: Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *Journal of Geophysical Research - Biogeosciences* **115**: G04011.

Lyons EA, Jin Y, Randerson JT. 2008: Changes in surface albedo after fire in boreal forest ecosystems of interior Alaska assessed using MODIS satellite observations. *Journal of Geophysical Research* **113**: G02012, doi:10.1029/2007JG000606.

Macias Fauria M, Johnson EA. 2008: Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society of London B* **363**: 2315−2327.

Matheron G. 1963: Principles of geostatistics. *Economic geology* **58**(4): 1246-1266.

Monteith JL. 1981: Evaporation and surface temperature, *Quarterly Journal of the Royal Meteorological Society* **107**(451): 1–27.

Mouillot F, Rambal S, Joffre R. 2002: Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biology* **8**(5): 423-437.

Nakićenović N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z. 2000: IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nasi R, Dennis R, Meijaard E, Applegate G, Moore P. 2002: Forest fire and biological diversity. In: Perlis A (ed.): Forest biological diversity. *Unasylva* **209**, FAO.

Pyne SJ. 2001: Fire – a brief history. University of Washington Press, Seattle & London, 204 pp.

Räisänen J, Eklund J. 2012: 21st century changes in snow climate in Northern Europe: a high-resolution view from ENSEMBLES regional climate models. *Climate Dynamics* **38**: 2575−2591.

Ripley BD. 1981: Spatial statistics. Wiley, New York.

Ruosteenoja K, Räisänen J, Pirinen P. 2011: Projected changes in thermal seasons and the growing season in Finland. *International Journal of Climatology* **31**: 1473−1487.

Saari E. 1923: Forest fires in Finland with special reference to state forests (in Finnish with an English summary and captions). Suomalaisen Kirjallisuuden Seuran kirjapainon O.Y., Helsinki.

Tanskanen H, Venäläinen A. 2008: The relationship between fire activity and fire weather indices at different stages of growing season in Finland. *Boreal Environmental Research* **13**: 285−302.

Tanskanen H, Venäläinen A, Puttonen P, Granström A. 2005: Impact of stand structure on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland. *Canadian Journal of Forest Research* **35**: 410-420.

Taylor, KE, Stouffer RJ, Meehl, GA. 2012: An Overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**: 485-498.

Tuomenvirta H. 2002: Homogeneity testing and adjustments of climatic time series in Finland. G*eophysica* **38**(1): 15-42.

Tuomenvirta H. 2001: Homogeneity adjustments of temperature and precipitation time series – Finnish and Nordic data. *International Journal of Climatology* **21**: 495-506, doi:10.1002/joc.616.

Vajda A, Venäläinen A, Suomi I, Junila P, Mäkelä HM. 2013: Assessment of forest fire danger in a boreal forest environment: description and evaluation of the operational system applied in Finland. *Meteorological Applications* (published online), doi:10.1002/met.1425.

van der Linden P, Mitchell JFB (eds). 2009: ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

Van Wagner CE. 1987: Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Petawawa Forest Experiment Station, Chalk River, ON, Forestry Technical Report 35.

Venäläinen A, Korhonen N, Hyvärinen O, Koutsias N, Xystrakis F, Urbieta IR, Moreno JM. 2014: Temporal variations and change in forest fire danger in Europe for 1960-2012. *Natural Hazards and Earth System Sciences* **14**: 1477-1490.

Venäläinen A, Heikinheimo M. 2003: The Finnish forest fire index calculation system. In Early Warning Systems for Natural Disaster Reduction, Zschau J, Kuppers A (eds). Springer: Berlin; 645–648.

Wallenius T. 2008: Past forest fires in Kalevala National Park and neighbourhood (in Finnish with English abstract). Metsähallituksen luonnonsuojelujulkaisuja. Sarja A 176, Metsäntutkimuslaitos, Vantaa.

Wallenius T. 2011: Major decline in fires in coniferous forests—reconstructing the phenomenon and seeking for the cause. *Silva Fennica* **45**: 139−155.

Williams KD, Senior CA, Mitchell JFB. 2001: Transient climate change in the Hadley Centre models: the role of physical processes. *Journal of Climate* **14**: 2659−2674.